

FORMATION OF GAS BUBBLES IN A STAGNANT LIQUID EXAMINED FOR THE TECHNOLOGICAL APPLICATION OF METAL FOAM

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ABSTRACT

A study of different shapes of gas bubbles rising in stagnant liquid experimentally. A testing facility with the high-speed camera was designed. The results obtained are presented in terms of dimensionless parameters i. e. Reynold's, Morton's and Eötvös. Factors varied to test their dependencies such as nozzle diameter (3 – 5 mm), rate of flow rate (15 and 130 l/h), viscosity, surface tension, and density were changed in order to see their effect on the shape of the bubble, its velocity in the liquid, surface tension force, drag force and buoyancy force. In order to vary such parameters, a water-ethanol mixture was used in the tank. Results showed at surface tension valued at 32 [N/m] it was not possible to trap air bubbles under the surface for the application of creating Foam, while 72 [N/m] it was possible, while for the tested flow rates most of Eötvös values were below one, which indicates that surface tension force dominates shape of the bubble when compared to gravitational force influence.

KEYWORDS: Bubble Shapes, Metal Foam, Eotvos, Viscosity, Speed Camera & Flowrates

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INTRODUCTION

Metal foam has been gaining popularity recently, Market demands have pursued new material solutions catering for a low specific weight, porosity, high stiffness, and impact absorption, as stated by V. C. Srivastava (2006) [1]. Which makes using metal foam attractive for modern industry manufacturers, Potential uses in light-weight applications including automotive, aircraft, and heat exchangers, accelerated such research from a niche solution to a currently highly commercialized utilization as surveyed by Bhatnagar (2017) [2]

The word “foam” has been used in many different connotations, thus there is a need to define it. Foam is the product of gas bubbles locked inside a liquid by the force of surface tension of that liquid. Yet as Banhart (2001) defined it, for most industrial applications the foam used would be Solid foam that has the cellular form [3]. could be used to clarify the different types of phase mixtures and the common nomenclature describing such mixtures.

Several ways are used to manufacture metal foam, it's in continuous increase according to market trends studied by Seeliger (2012) due to market demand for lower specific weight with high stiffness for aluminum foam sandwich [4], or ability to absorb sounds in acoustic applications due to its porous structure as stated by Jorge P. (July 2010) [5]. One main process to manufacture the foam is by gas injection, in which the metal foams are directly fabricated by injecting a pressurized gas in the molten metal, for this approach several factors are considered influencing for the process to be carried out successfully, for example, the viscosity of the molten metal, viscosity pressure of gas injected. The viscosity of the metal is usually controlled by adding some salt or powdered

ceramic like (Al₂O₃/SiC) as shown by N. Babcsan J. (2003) [6].

Currently, there are studies giving satisfactory results using empirical equations to describe the shape, aspect ratio of a rising gas bubble in stagnant liquids, shapes and terminal velocities of bubbles rising in viscous liquids. Such studies were used to pave the way for this paper such as the one analysing Morton numbers (Mo) greater than 4×10^{-3} showing that the drag coefficient and dimensionless bubble shape are functions only of Reynolds number (Re) in a study published by D. Bhaga in Journal of Fluid Mechanics (1981) [7], or another by J. R. Grace (1976) that surveyed the parameters used to characterize the shape of rigid particles, and the factors that determine the shape of bubbles and drops [8]. Examples for studied influencing factors are viscosity of the liquid, surface tension, volume flow rates, and nozzle diameters, using several approaches in defining main parameters for the shape of the bubbles. experimental studies like the one studying individual bubbles of 2.5 mm in diameter produced at a capillary tube filled with water containing froth, polymer or inorganic salt, where bubble aspect ratio (shape) and rise velocity were measured by M. Maldonado (2013) 1.2 m above the point of generation [9]. similarly, experimental studies of the bubble trajectory in three-dimensional space, that was deduced by analyzing the bubble characteristics in the two-dimensional plane. This was captured by a single high-speed camera and the bubble trajectory in the water was ascertained by this method explained by Hongjie (April 2015) [10] and the experimental study of deformation of gas bubbles rising in different liquids over a wide range of Morton numbers, from 1×10^{-11} to 1, in relation to bubble diameters by T. Maxworthy (1996) [11], all provided an image for what experimental data is available to base this study on. Also numerical publications were studied, for example, VOF-based numerical method for simulating mass transfer across deformable fluid interfaces, with the underlying mathematical model based on continuum thermo-mechanics, allowing for different solubilities of the species in the respective fluid phases by Dieter Bothe (September 2013)[12]. The dynamics of a bubble, initially stationary and spherical, rising in a viscous Newtonian liquid studied numerically using 3-D Volume-of-Fluid (VOF) method implemented in the Gerris flow solver by Monica Gumulya (February 2016) [13], numerical method combining the volume fraction data obtained from a primary multi-fluid simulation with simple and efficient secondary bubble simulation by Ren, B. (2015)[14] and theoretical studies like the one by A. TOMIYAMAA (2007) for analysis to determine dimensionless groups that influence single isolated gas bubble's velocity in a stagnant liquid, rising in a large container filled with different viscosity liquids [15], or on the pressure developed in a liquid during the collapse of a spherical bubble in the stagnant liquid by Lord Rayleigh in (1917)[16]. Also, studies using same dimensionless parameters that shall be used in this paper like Morton's by M Pfister (2014) [17] Eötvös [18] by Viana (2003) and Reynold's, which have been proven to correlate strongly with the studied properties as bubble velocity and aspect ratio, that are analysed in this paper.

Due to the difficulty to test bubble shapes in molten metal for the application of metal foam, the process was simplified into water and air, yet same metal foam influencing parameters are studied in this paper, such as viscosity, surface tensions, Mo, Eo and Re dimensionless parameters.

In this paper formation of gas bubbles for the purpose of creating foam shall be examined and its relation to several influencing factors, also volume flow rate and its contribution to the bubble shape, the visualization is initially created by the usage of a High-Speed camera.

Experiment Set-Up

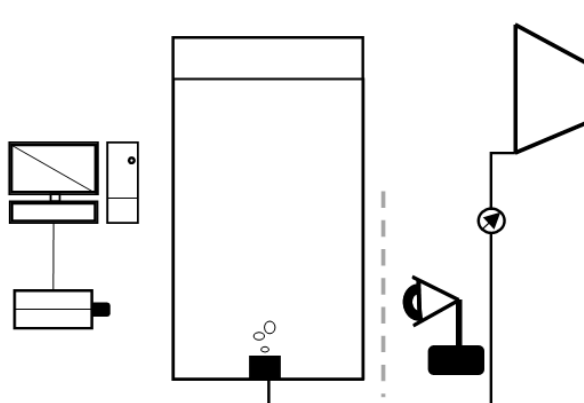


Figure 1: Experimental Setup

From the illustrated figure 1, a glass water tank of dimensions 30 x 20 x 20 cms, glass thickness is 3 mm, filled with liquid. An air compressor is connected by tubes inside the water flow could be adjusted anywhere between 15 to 200 l/h. The flow rate is observed using the flow meter and by connecting the speed camera to a computer. Images of the frequency of 130 Frames per second are sufficient to see how the shape of the air bubble will evolve., There are mainly 2 modes of airflow from the air pump, one of which is of a low flow rate (15 l/h) and in that phase, it is noticed that air bubble does not merge during the ascend to the surface of the tank. On the other hand for the second mode, the flow 130 l/h and in this case it is observed air bubble merging into bigger bubbles, velocity is hard so for the goal of foaming the liquid, a low flow rate is more important to be studied clearly.

As part of this study, surface tension and viscosity decrease with an increase in temperature as stated by Yilmaz (2011) [19], in case of using water it was at 24 °C. In the case of using Ethanol-water mixture in order to study the effect on viscosity on the shape of the gas bubble by A. Nikumbi (2013)[20] in which an exothermic reaction was observed, the speed camera acquisitions were made at a temperature of 25 °C.

For the usage of speed camera at high number of frame per second (130-180FPS) it was required to have a higher than ambient light intensity, and this was achieved by using a LED light source with several diodes with varying light intensity, and a piece of parchment paper was used as a light diffuser, without the light diffuser the images had a high image-contrast difference which made calibrating the pixel to length value hard, since one area where the light was focused was bright, while the rest of the tank remained too dark to analyze, the use of a light diffuser made the image obtained by the speed camera more homogenous when comparing dark pixels to light pixels and gave more accurate results.

METHODOLOGY

Image Acquisition Equipment

A speed camera with a separate light source has been used, different acquisitions were taken for different FPS, the camera could take as many as 1200 FPS, yet 130 FPS to 180 FPS were enough to trace different shapes of gas bubbles. The camera was connected to a computer and using provided software it was possible to have a slow-motion video of the gas bubble, the exposure, FPS, sample time could be changed through the camera software, while the focus has to be adjusted manually through an externally attached lens.

It is noted that the high-intensity light source was required for the experiment, the higher the FPS value the higher

intensity was required through the light source [20].



Figure 2: Image Processing Software

Image Processing Software

In order to calculate bubble size, velocity and distance traveled it was required to use image processing software, which can process RAW format images. Open-source, Java-based software was used, in which it is required to define a horizontal and vertical Pixel to unit ratio, in which the software can measure a number of pixels, and if those pixels form a shape of a known length, then it possible to measure the size of any object on the image, given reference object and measured object are at equal distances from the camera lens. This method was used for calculating diameter, and distance traveled by the bubble from the nozzle, by obtaining the time of the image frame from the camera it is possible to calculate the velocity of the air bubble, also the acceleration, and those results were incorporated into calculating dimensionless numbers used for describing the shape of the bubble later on in this paper.

Dimensionless Parameters

For the representation of the results of this experiment, several parameters were chosen in order to describe the air bubbles and make this study relevant and comparable to other published papers. In this part, those parameters will be defined with some explaining to the significance of this parameter.

Reynolds Number

$$Re = \frac{\rho u L}{\mu}$$

where ρ is the density of the fluid (SI units: kg/m³), u is the velocity of the fluid with respect to the object (m/s), L is a characteristic linear dimension (m), in this case it would be diameter of the bubble and μ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/m·s).

The most common use of Re is determining whether this flow is laminar, transitional or turbulent, Low Reynolds numbers occur when a flow has dominant viscous forces, it's constantly moving, at lower velocities. While Turbulent flows are characterized by high values of Reynolds number (more than 1500) which could mean the flow contains eddies, vortices, and other flow turbulences.

In this study, the significance of Reynolds number is to measure how turbulent is the flow around the air bubble, and thus it is possible to quantify the influence of the turbulence on the deformation on the bubble shape or its aspect ratio.

Morton Number

$$Mo = (g\mu_c^4 \Delta\rho)/(\rho_c \sigma^3)$$

g is the acceleration of gravity, μ is the viscosity of the surrounding fluid, ρ the density of the surrounding fluid, $\Delta\rho$ the difference in density of the phases and σ is the surface tension coefficient.

Morton number was developed during a dimensionless analysis for an experiment of a bubble rising in a stagnant fluid, and it is based on the combination of Weber and Froude numbers.

Eötvös Number

$$Eo = \frac{\Delta\rho g L^2}{\sigma}$$

$\Delta\rho$: difference in density of the two phases, g : gravitational acceleration, L : characteristic length, could be considered bubble diameter here and σ : surface tension.

Eötvös number could also be called bond number and it describes the ratio of forces to gravity to surface tension influence in the shape of the bubble.

RESULTS

Table 1: Comparison between 2 Case Studies

Flow rate [l/h]	15	130
Nozzle Diameter [mm]	3	5
surface tension [mN/m]	72	72
Morton's Number	1.59527E-11	1.59527×10^{-11}
Kinematic viscosity [m ² /s]	105×10^{-8}	105×10^{-8}
Sample time [s]	0.275	0.32

The experiment was carried out at different parameters, 3 cases are to be shown through the results part, first 2 cases are compared where the liquid used is water D5V130 and D3V15, where D5 means nozzle diameter is 5 mm, and V130 corresponds to a volume flow rate of 130 l/hr, below table shows the 2 compared cases

Comparison between D5V130 and D3V15

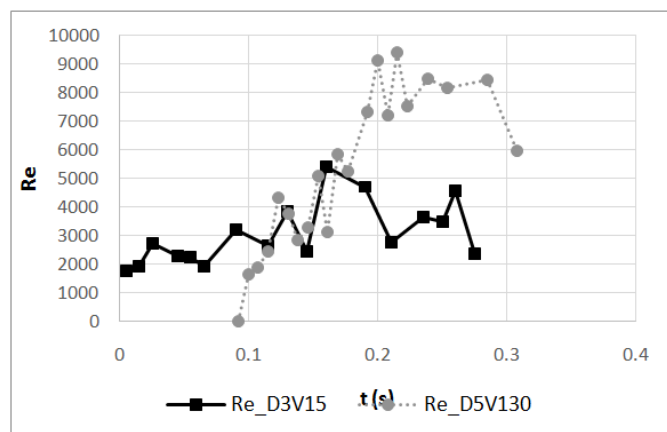


Figure 3: Reynold's Number Values of Nozzle Diameter 3 mm. and Flowrate 130 l/h Compared to D3V15

Figure 3 shows a comparison for D5V130 (nozzle diameter of 5mm, flow rate of 130 l/h) and D3V15, indicating Reynold's number variance with time. For D5V130, the first peak occurs at $t = 0.12$ is when the bubble reaches maximum diameter before it detaches from the nozzle, notice that the diameter increases once more when the second bubble merges into the first, and then it keeps increasing as the bubble rises to the surface. The maximum value of Re is 9418 at $t = 0.215$ s and it could be explained as when the bubble merge occurs, turbulence is high as the second bubble is pushing the gas/liquid boundary to influencing the diameter to increase, diameter.

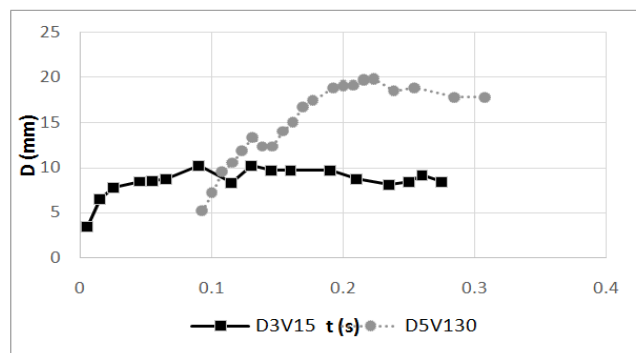


Figure 4: Diameter Values of Nozzle diameter 3 mm and Flowrate 130 l/h Compared to D3V15

D3V15 values are noticed to be much lower than that of higher flow rate, with the peak in Re ($Re = 1067$, $t = 0.16$ s) coincide with the maximum velocity. Noted from the change in Diameter (figure 4) and Re , the flow could be described as mostly laminar and this was better optimum to describe the formation of the gas bubble with minor influence from unmonitored factors, such as bubble merging or splitting, drag forces due to high flow by the gas bubble. When calculating the characteristic length for Re , the radii of the ellipsoidal were used to calculate volume and area, which were divided to get the characteristic length, which should give a more accurate value.

Figure 4 is a plot of the relation between diameter and time. The diameter was measured as a mean diameter for the bubble of a varying radius. The highest rate of increase of radius with respect to time could be noticed when merging happens, after than the instant of the biggest radius is very close to the instant of highest Re number which could be contributed to turbulence and expansion of the gas-liquid boundary due to the merging of the 2 bubbles. It is observed that for higher flow rates the diameter is bigger, at a certain time, $t = 0.13$ for D3V15 (Diameter = 3 mm, flow rate = 15 l/h) the diameter has minor fluctuations and could be considered stabilized, but when analyzing the radius for the higher flow rate (D5V130) the diameter seems to hardly achieve stabilization, this could be related to higher turbulence, and merging of air bubbles.

Bubble Shapes



Figure 5: Speed Camera Acquisitions

For 130 l/h flow

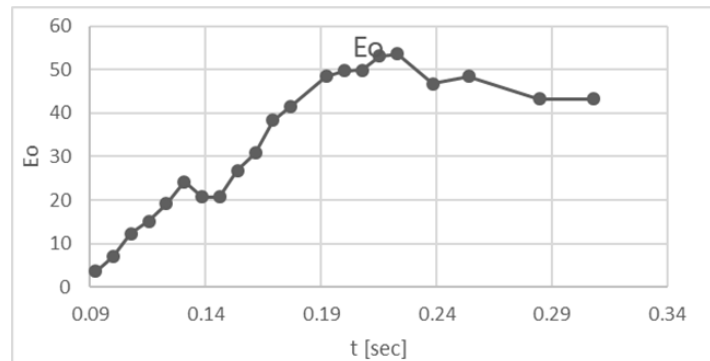


Figure 6: Eötvös Number

Figure 5 shows cropped acquisition images from the speed camera at different instances, the 3 pictures depict different stages of the process of bubble merging, it can be noticed at $t = 0.138$ s that the first bubble has already detached from the nozzle outlet, and at this stage the bubble speed decreases till the second bubble is merged into the first ($t = 0.154$ s) which leads to an increase in Reynold's number (figure 3 at $t = 0.154$) then the last picture shows when the merged bubble with bigger diameter starts ascending by buoyancy force to the surface.

Figure 6 depicts a change of Eötvös number (bond number) with time, it should give an estimate of how prevalent gravitational forces compares to surface tension forces, and in the plot most values are higher than 1, which would express that gravitational force is more influential to the gas bubble shape than surface tension force, while at early time instances where values are closer to 1 it could mean there is a balance between surface tension and gravitational forces in defining the shape of the bubble.

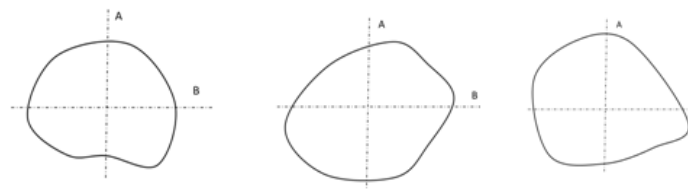


Figure 7: Bubble Shape Change w Time

Table 2: Table Showing Properties Corresponding to Bubbles in Figure 7

Time [s.]	0.045	0.09	0.16
A [mm]	6.9	8.4	9.1
B [mm]	10	11.93	10.17
Distance Travelled	15.2	28.636	55.9
Velocity [m/s]	0.285	0.33224	0.593333
aspect ratio	0.69	0.704107	0.894789
Eo	0.253811	0.369628	0.348421

For 15 l/h flow

Figure 7 shows bubble shapes for nozzle diameter = 3 mm and Volume flow rate if 15 l/h for this acquisition it

was noticed that the bubbles rise uniformly, in a steady state. The bubble would start at the nozzle mouth in the shape of a mushroom head, and as it rises it would take a more spherical shape till mid-distance where some wobbling occurs, a significant amount of bubble remained trapped under the liquid surface, and that could point out that the surface tension of water is adequate for forming foam with bubbles of properties described.



Figure 8: Bubbles Trapped under Water Surface

Figure 8 shows image acquired through the speed camera showing for a flow rate of 15 l/h it was possible to trap the air bubbles in the liquid surface.

Aspect ratio is a good way to deduce how uniform is the bubble shape, also several empirical equations have offered equations for the bubble velocity in a relation to the aspect ratio such as the study by Baz-Rodriguez (2012) [21]

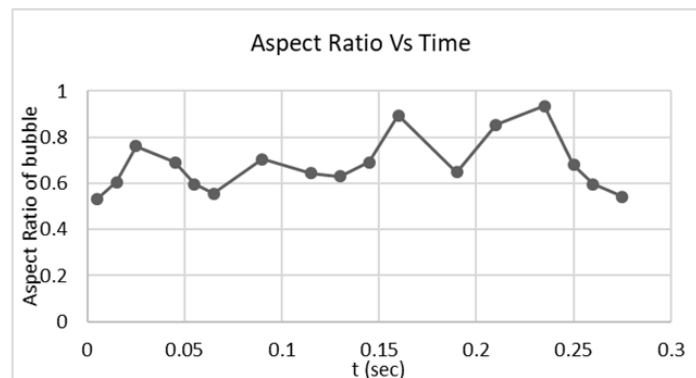


Figure 9: Aspect Ratio vs Time

Figure 9 shows the change of aspect ratio of the gas bubble versus time. The values at many time instances seem to approach 1, which could make it seem that the bubble is more spherical-like

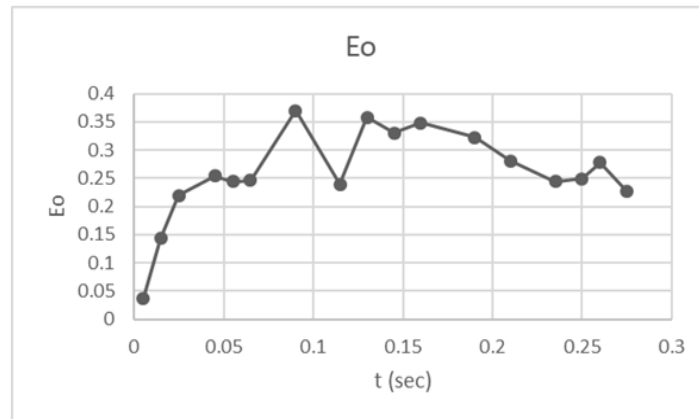


Figure 10: Eotvos Values Change with Time

Eötvös describes the effect of gravitational forces compared to surface tension forces when observing figure 10. It shows all values are below 1, thus it could be assumed that surface tension at the liquid-gas boundary of the bubble is highly influencing the resultant shape when compared to gravitational forces.

Table 3: Showing Properties for Case of Gas Bubbles in Water-Ethanol Mixture

surface tension [mN/m]	31
Morton's Number	5.65826E-09
kinematic viscosity [m2/s]	2.14938E-06

Water-Ethanol mixture with the nozzle diameter of 3mm and $v = 15$ l/h

The idea behind adding ethanol to the water is to study the effect of changing the values of viscosity, surface tension and density on the shape of the air bubble and examine the interaction between different gas bubbles, for the reason it was required to measure or calculate those values, there were no equipment ready for this purpose, thus using volumetric ratios, it was possible to postulate those values.

in order to achieve a viscosity of 2×10^{-3} Pa. s, it is required to obtain a molar fraction of ethanol of 0.13, this attained by mixing 8 liters of water (444.1 moles) and 3.875 liters of Ethanol given it's pure (66.359 moles) – the used Ethanol was with 95% purity, that was also taken into consideration.

The Ethanol water Mixture should affect the values of density, surface tension, and viscosity, for the mixture the density was taken by 930.5 kg/m³ [20]

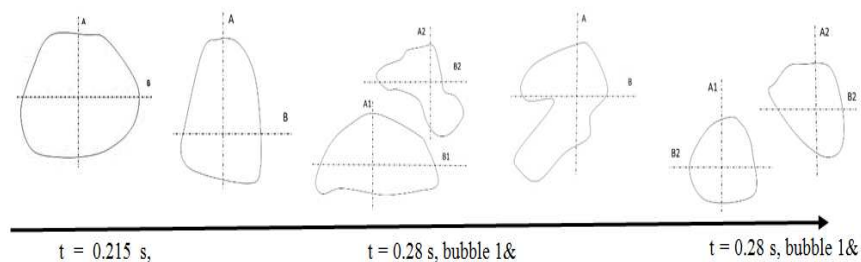


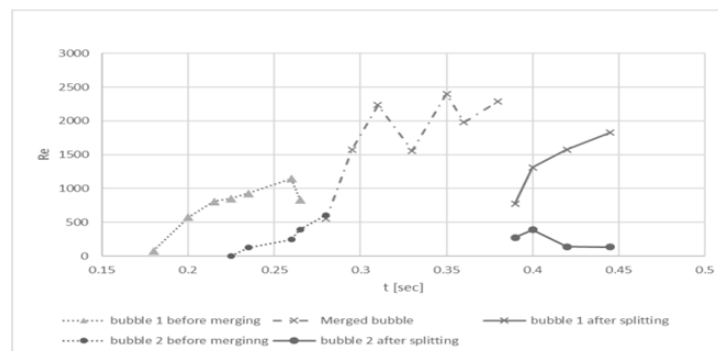
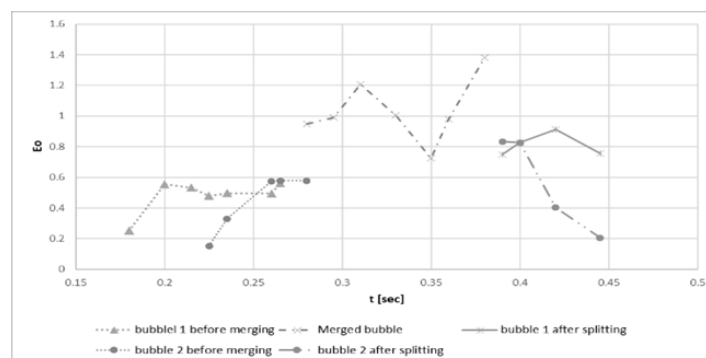
Figure 11: Bubble Shapes

Table 4: Properties of Corresponding Bubbles in Figure 11

Time (sec.)	0.215	0.26	0.28		0.295	0.4	
			bubble 1	bubble 2		bubble 1	bubble 2
A (mm)	7.2	5.56	11.5	10.4	11.1	10.1	12
B (mm)	9.14	12.242	10.1	7	10.92	10.01	8.6
Distance	11.8	23.415	30.6	32.6	35.2	70.6	76
velocity (m/sec)	0.213333	0.2766	0.109286	0.6	0.306666667	0.28	0.5
aspect ratio	0.787746	0.454174	1.138614	1.485714	1.016483516	1.008991	1.395349
Eo	0.532368	0.494362	0.946585	0.578105	0.990850401	0.826485	0.82654

It is worth stating that after the ethanol was added to water, the viscosity has increased, yet surface tension of the liquid was decreased. Also mixing water and ethanol would lead to an exothermic reaction which leads to an increase in temperature which was taken into consideration, by the usage of the thermometer. So most of the acquisitions were measured at room temperature around 25 °C, Surface tension value was taken as 31 mN/m/, given the molar ratio [19]

In Figure 11 stages were divided according to the merging and splitting of the bubbles, as it was thought that would be the best way to describe this phenomenon, also it would be better to coordinate such stages with the graph.

**Figure 12: Re vs Time****Figure 13: Eötvös vs Time**

Change of Re with time is described by figure 12. It is noticed that the area with the highest turbulence with Re values ranging between (500 and 2500) is in the merged bubble part, bubbles before and after merging have a generally lower Re number. One of the bubbles after splitting seems to have significantly lower Re number as they approach the surface of the water tank.

Figure 13 is concerned with variations of Eötvös number with time, as the merging of the gas bubble increases the mass, it is obvious that before and after merging surface tension force dominates the shape of the bubble, while at the

merged state the gravitational force dominates which could correlate to the increased mass of the air bubble. For bubble 1 before merging values vary between 0.21 and 0.58, then after splitting bubble, it is around 0.7 to 0.9 while that for bubble 2 it is from 0.18 to 0.6, and after splitting it changes from 0.83 to 0.2. For the merged bigger bubble is varies between 0.9 and 1.4.

CONCLUSIONS AND DISCUSSIONS

Eötvös number increases as the rate of flow rate increases, as there was a significant increase in the values of Eötvös number (10 to 55) when the flow rate was 130 l/h, while when the rest of the results were acquired at an air volume flow rate about 15 l/h Eötvös were around 1, a much higher values than one could indicate that the dominant factor influencing the shape of the gas bubble is gravitational force, which could also be linked that at a higher flow rate the size and also the mass of air bubbles is higher.

It is also noticed that the effect of bubble merging depends on both the flow rate and the fluid properties, as for the first acquisition at 130 l/h, bubble merging was prevalent that seems that isolating a single bubble for analysis was hard, and at the 15 l/h it was easier to analyze a single bubble, yet there was dependency on viscosity and surface tension since when ethanol was added to the water, even at a low flow rate of 15 l/h merging between the air bubbles occurred

When comparing from the perspective of Morton's number, it could be said that for Morton's number of 1.595×10^{-11}

It was possible to trap air bubbles under the surface of the liquid, no interference occurred between the air bubbles, but at same nozzle diameter (3 mm), flow rate 15 l/h, but changing viscosity, surface tension and density making Morton's number of 5.658×10^{-9} bubbles were not trapped under the liquid surface, while interference still happened between the bubbles.

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